Status of the LHC Inner Triplet Quadrupole Program at Fermilab

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Abstract—**Fermilab, in collaboration with LBNL and BNL, is developing a quadrupole for installation in the interaction region inner triplets of the LHC. This magnet is required to have an operating gradient of 215 T/m across a 70mm coil bore, and operates in superfluid helium at 1.9K. A 2m magnet program addressing mechanical, magnetic, quench protection, and thermal issues associated with the design was completed earlier this year, and production of the first full length, cryostatted prototype magnet is underway. This paper summarizes the conclusions of the 2m program, and the design and status of the first full-length prototype magnet.**

***Index Terms*—cryogenics, quadrupole, superconductivity**

I. Introduction

The Fermilab contribution to the Large Hadron Collider (LHC) at CERN includes half of the high gradient insertion quadruple magnets which provide the final focus at the four interaction regions. Over the course of the past year, work at Fermilab has seen the completion of the 2m model magnet program used to develop and prove the production design, including the completion of testing the final 3 models. In preparation for production of the 5.5m magnets that will be delivered to CERN, Fermilab is building the first full-length prototype magnet. This will be assembled using production tooling, placed in a prototype cryostat, and tested in the horizontal test facility. At the time of this writing, the coils for the first prototype magnet have been wound and cured, and are being prepared for collaring. This paper describes the major conclusions of the model magnet program, the changes in the baseline magnet design made as a result of that program, and the status of the production of the first prototype.

Manuscript received September 18, 2000. This work was supported by the U.S. Department of Energy.

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II. Model Magnet Program

A. Design and Acceptance Criteria

Over the course of the past 3 years, Fermilab has developed the design [1,2,3] and, in conjunction with CERN, the performance criteria for the MQXB quadrupoles for LHC. With the completion of the HGQ model magnet program, it has been demonstrated that the magnet design meets all of the requirements.

Figure 1 shows the quench performance of all model magnets, HGQ01 through HGQ09, tested between March 1998 and March 2000. Each production magnet must be trained to 230 T/m in the initial thermal cycle, and reach 220 T/m without quenching following thermal cycles and quenches with full energy deposition. The maximum operating gradient given by the machine optics is 215 T/m.

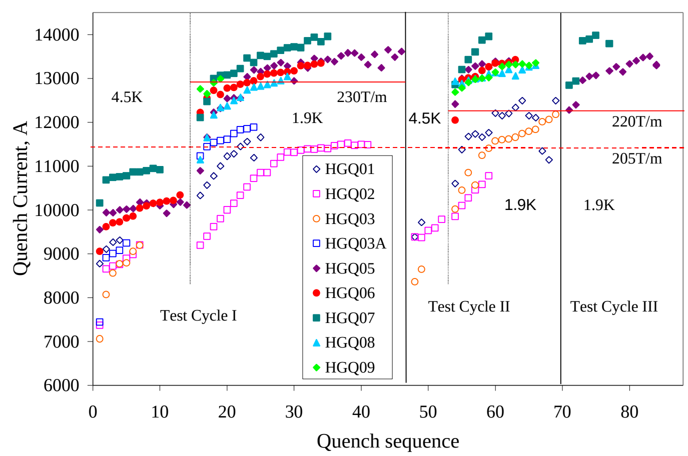

Figure 1. Quench performance at 4.5K and 1.9K for all model magnets, through all thermal cycles. Magnets HGQ01 through HGQ07 were tested at 4.5K prior to 1.9K testing. Magnets HGQ05 and HGQ07 were tested in a 3rd thermal cycle to investigate the effect of longitudinal restraint.

Initial training results of magnets HGQ01 through HGQ03 were not satisfactory. In HGQ01, the quenches were located dominantly in the body to end transition. They are believed to be induced by the large shim placed at the midplane of the inner coils (350-425 µm), and removed from the pole of the outer coils (225 µm) to achieve the desired prestress. This resulted, however, in a significant discontinuity at the body to end transition. In HGQ02 and HGQ03, the quench locations were in the magnet ends. This was due to the use of Ultem end parts, which have a large thermal contraction mismatch relative to the coils. Magnet HGQ03A, a rebuild of HGQ03, demonstrated that increased longitudinal restraint by introducing collar / yoke interference was not sufficient to overcome this deeper rooted problem.

Starting with HGQ05, a set of design changes were introduced, and the quench performance of the magnets has consistently met the requirements since. Most important of the changes were the re-introduction of G10/G11 end parts, which are much better matched in contraction to the coils; and the detailed understanding of the target coil size, such that properly sized coils were achieved through the curing process. In HGQ05 through HGQ09, a shim of zero to 25 microns at the pole was typically required to achieve the desired prestress. In a single case 50 microns was added to a coil. Other valuable changes and experience gained in these magnets included: control of coil size variations along the length of each coil through the use of local shims in the curing mold; proving good quench performance can be achieved for warm prestress in the range of 55 to 100 MPa; the use of welded collar packs to increase the out of plane rigidity of the collar laminations relative to the coils; and the insensitivity of quench performance to the presence or absence of end restraint. Finally, in both HGQ08 and HGQ09, stamped collar laminations of the final design were used. These laminations allowed the removal of the bearing strips from the design. No effect was noted on quench performance [4].

Figure 2 shows selected harmonics data for each model magnet. Field quality improved as the coil size targets were determined and achieved, and from magnet HGQ05 and on, the harmonics of the model magnets have been of accelerator quality [5]. The harmonics data are used to develop reference tables, as an estimate of the MQXB production set of harmonics. Based on the ensemble of data across all harmonics and model magnets, in the as built form, the error table estimates were refined and updated to tighter tolerance values. Detailed tracking studies using the revised reference tables have resulted in the elimination of several corrector layers in the triplet, and a simplification of the overall system.

The ramp rate dependence of each model magnet is shown in Figure 3. Although the magnets nominally operate at a ramp rate of 10A/s, and each model shows no degradation at this rate, the ramp rate curves are indicative of two issues that were studied and solved late in the model program. First, the increased ramp rate dependence seen in magnets HGQ06 and HGQ07 is due to the use of a 190C, high pressure cure cycle necessitated by the use of polyimide adhesive on the cable insulation and the need to achieve the desired coil size. This cure cycle produced low and variable interstrand resistance, and resultant large eddy current effects. HGQ09 demonstrates the solution, where using uncoated, unannealed cable a 2-step cure cycle was introduced. First setting the adhesive using a 190C / low pressure step, followed by setting the coil size with a 135C / high pressure step, the ramp rate dependence returns back to that seen in the early models.

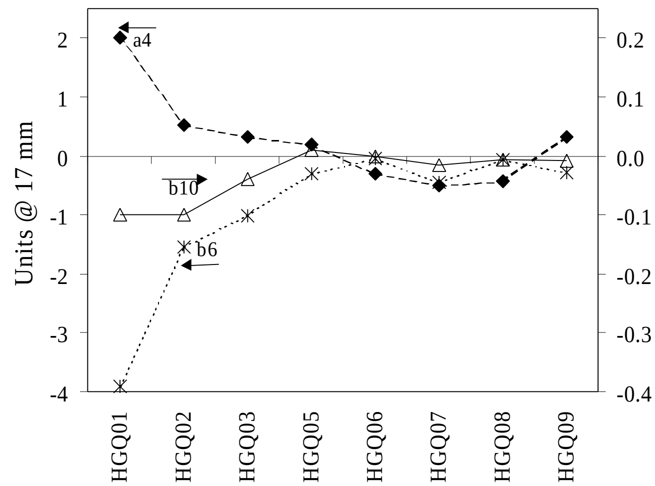

Figure 2. a4, b6 (left hand scale) and b10 (right hand scale) as measured for all model magnets.

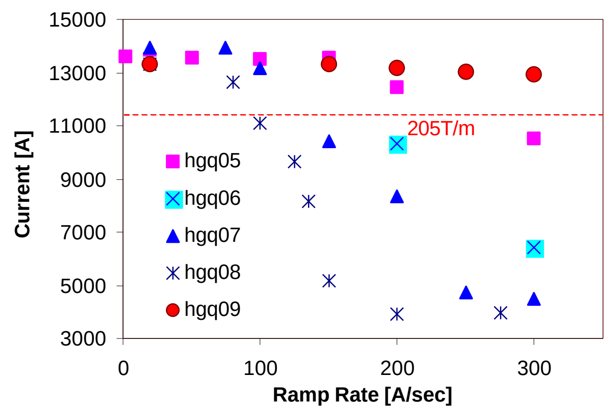

Figure 3. Ramp rate dependence of model magnets HGQ05 through HGQ09. The LHC operating point is 10A/s. HGQ05 ramp rate quenches above 200A/s were in the inter-layer splice, improved cooling removed this problem. HGQ06 and HGQ07 used uncoated cable in a high temperate and high pressure cure cycle. HGQ08 used Stabrite coated cable in a high temperature, high pressure cure cycle. HGQ09 used uncoated cable in a two-step cure cycle.

In HGQ08, Stabrite coated cable was used in an attempt to better control the turn to turn variation in the interstrand resistance. While better control was achieved, the solution in HGQ09 is simpler for us to effect. However, the low and controlled interstrand resistance of HGQ08 allowed for the performance of thermal margin studies, confirming the adequate thermal margin of the design for use at the high luminosity interaction points [6].

The model magnet program included an extensive study [7] of the quench protection system using various heater configurations, placed both between the coils and on the outer radius of the outer coil only. Figure 4 shows the voltage required is consistent and low across all tests. Temperature rises were always less than 400K, even for quenches induced in the outer coil midplane. These results show that using heaters located over the outer coil only, the MQXB will operate well within LHC parameters.

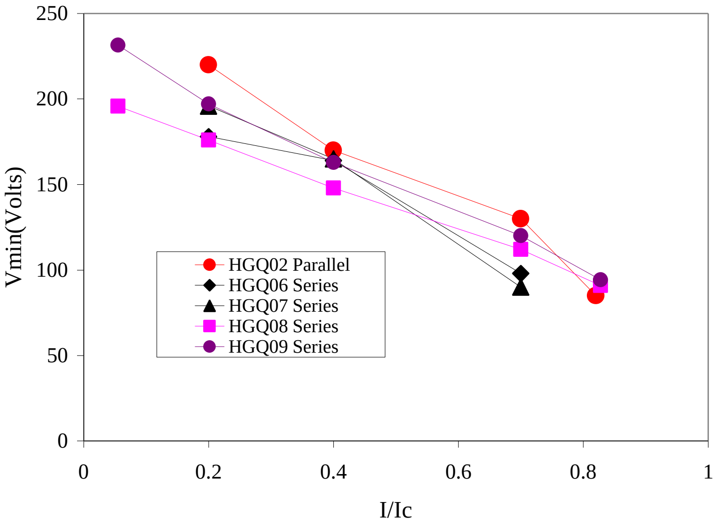

Figure 4. Voltage required to quench a model magnet as a function of fraction of critical current.

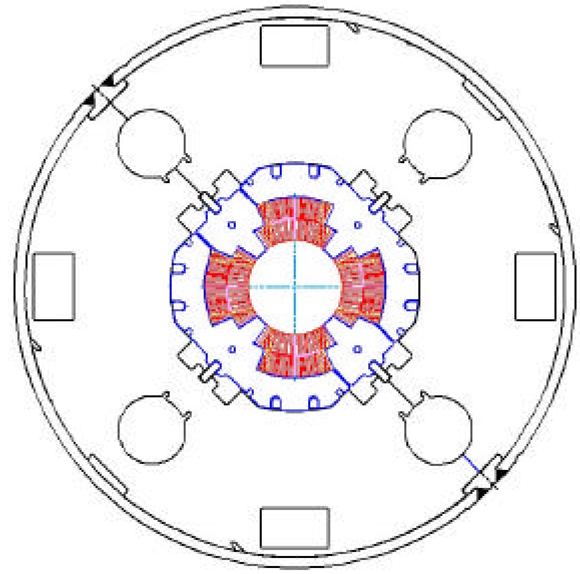

Figure 5. Prototype MQXB cross-section.

In conjunction with the tests of HGQ08 and HGQ09, several busbar experiments were performed that confirmed the design [8] of the main bus which will be used throughout the inner triplets.

III. Full Length Prototype

A. Prototype Plans

The assembly of the first full-length prototype is underway. This magnet is being made using the production tooling, to the final lengths, and will be tested horizontally in a production type cryostat, using a new test facility just being completed. The major differences between the prototype and production magnets are the diagnostic instrumentation present only in the prototype, and the correction elements present only in the production magnets.

B. Cold Mass Design

The baseline design of the prototype magnet is shown in Figure 5. It consists of a two-layer coil, completely supported by steel collars, and surrounded by an iron yoke for flux return. The whole assembly is contained with a steel shell, which is welded twice around the perimeter for closure and alignment. The body magnetic cross section is unchanged from the original baseline.

The inner coil is formed from 37 strand Rutherford cable, using SSC type wire which is uncoated and unannealed. The outer cable is 46 strand Rutherford cable, again from uncoated and unannealed SSC type wire. Both cables are insulated with two wraps of Kapton insulation, with the outermost wrap including a polyimide adhesive. The end parts are of G11CR. The additional inner coil end current block introduced with HGQ06 has been kept, which provides some improvement in the end harmonics. The coils are cured in a two step cure cycle, which sets both the interstrand the resistance and the coil size properly. Mechanical support of the coils is provided by Nitronic 40 collars which are stamped, and pre-assembled into 37mm long packs and provide the required rigidity and cooling channels. The collars are keyed with 8 phosphor bronze keys, to a target warm azimuthal prestress of 75MPa in both the inner and outer coils. Prestresses in the range of 55 to 100MPa are known to produce acceptable quench performance. The coil ends are supported by G11CR spacer blocks squeezed by tapered aluminum end cans, to a prestress equal that in the region nearest the body, and tapering off at the coils ends. The aluminum end cans are anchored to the magnet end plates as a positive means of controlling the magnetic length.

C. Cryostat Design

The cryogenics system for the inner triplet system have been described elsewhere [9]. The inner triplet cryostat will mechanically support and thermally insulate the Fermilab or KEK cold mass, the external heat exchanger system, cryogenic piping, BPMs, inter-magnet absorbers in the high luminosity interaction points, and will provide alignment fiducials such that the magnetic axis of each component is understood. The prototype cryostat design, shown in Figure 6, is closely related to the production design, with the exception that all provisions for the correctors, BPMs, and absorbers, which are required for the production models, have been removed.

A major component of the design is the external heat exchanger, which provides the necessary cooling to the cold masses of the inner triplet to 1.9K. The inner triplets are exposed to a large amount of beam heating, approximately 180W over 30m. An internal heat exchanger design, similar to that in the main LHC magnets, would have required 2 or more parallel cooling paths in each cold mass. Furthermore,

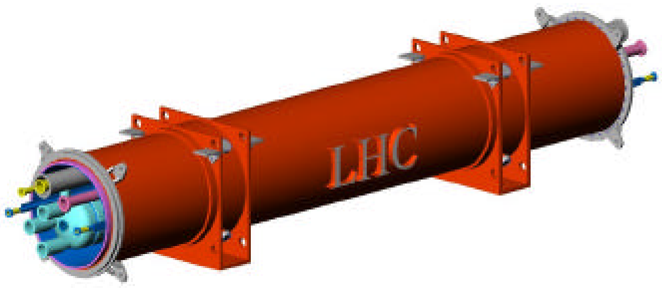

Figure 6. Prototype Inner Triplet Cryostat

the number of quadrupole and corrector cold mass types within the triplet made the separation of the cooling channel location from the cold mass highly desirable. The use of the external heat exchanger is an extrapolation of the LHC arc design, and relies on conduction through the pressurized superfluid to transport the deposited energy to the two phase superfluid passing through the system. This system design is described in detail elsewhere [10], and tests have confirmed the adequacy of the copper corrugation used in the heat exchanger [11]. Recently, a full scale test of the system, designed by Fermilab, constructed in industry, and tested at CERN, has confirmed the overall performance of the system for the LHC.

D. Status

Currently all of the outer coils and ¾ of the inner coils for the prototype have been wound and cured. The coil winding machine and curing press are from the SSC, with new contact tooling designed as need be for the quadrupole design. Using cable remnants from the model program, the coil winding and curing processes were practiced before commencing with the prototype coils. As is illustrated by Figure 6, some break in of the tooling was seen. A continuing issue just resolved has been the efficiency of the coil winding machine, which needed some software upgrades after 10 years of non-use. The production curing molds show better uniformity than those used in the model magnet program, and currently no local shimming is used to improve the coil size uniformity.

The cryostat parts for the first prototype are all either in house or on order, and a horizontal test stand has been recently installed and will be commissioned shortly. The test of the prototype is expected to start around the end of the year.

ACKNOWLEDGMENT

The authors thank the staff of Fermilab's Technical Division who have worked so hard on this effort over the course of the past years.

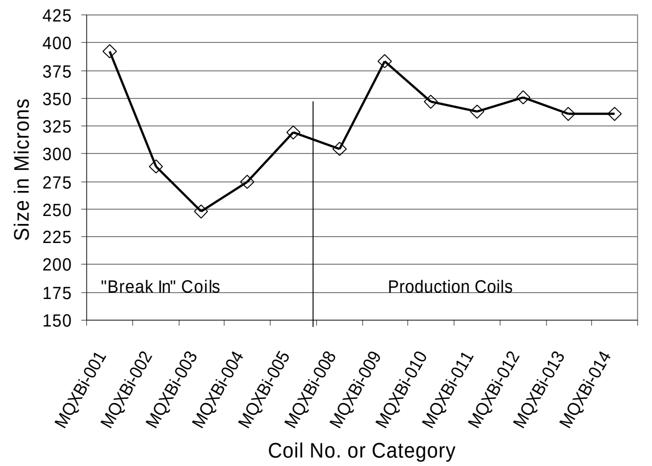

Figure 7. Average coil size relative to a steel master for long inner coils fabricated to date. Break In coils were made each made from different remnants of cable from the model magnet program.

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